

Magnetization Structure at Buried Interfaces

presented at

Workshop on Nanomagnetism
using X-ray Techniques
August 29 – September 1, 2004
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by

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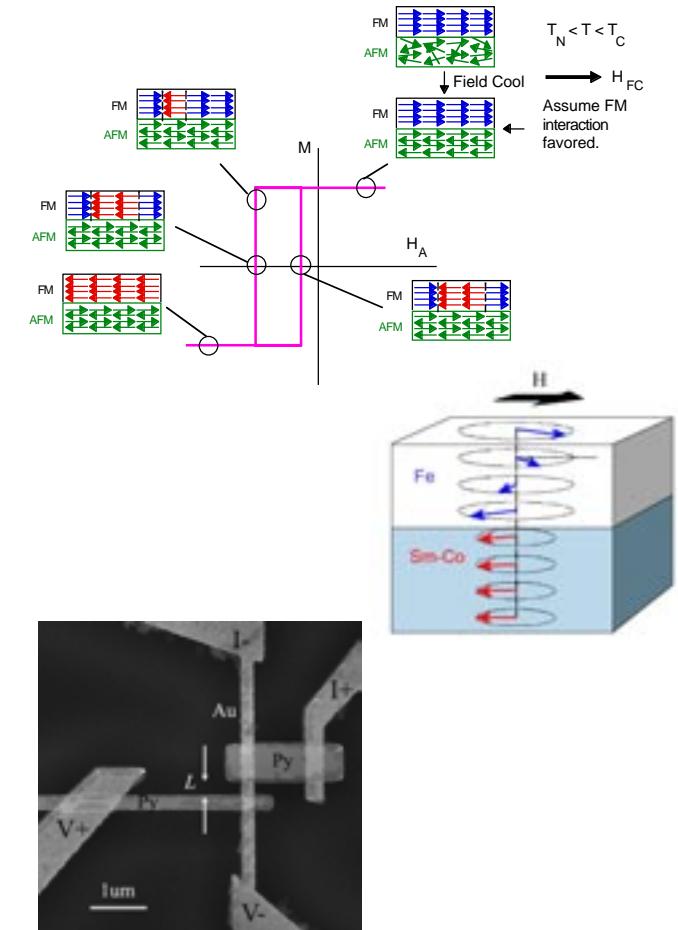


Outline

- **Motivation**
- **Equilibrium Properties at Interfaces**
 - Induced Magnetization
 - Suppressed Magnetization
- **Non-equilibrium situations**
 - Metastable configurations
 - Spin-injection
- **Conclusions**

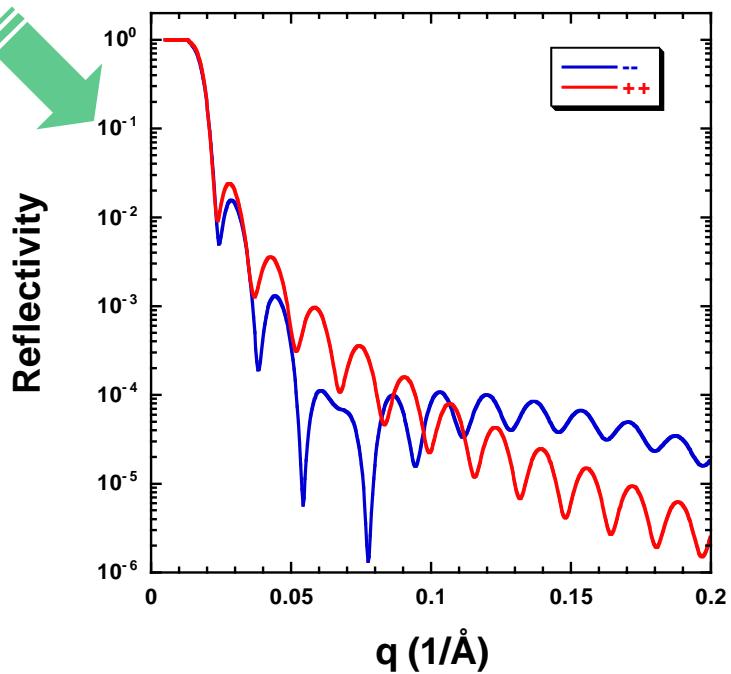
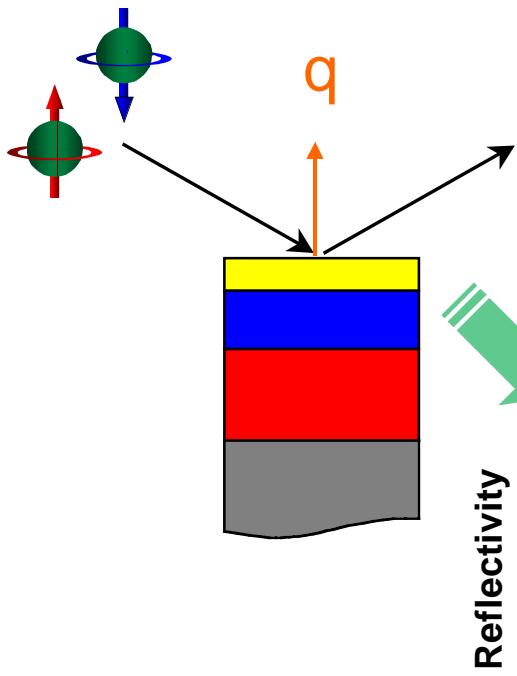
Interfaces are central to Nanomagnetism

- **Antiferromagnetic / Ferromagnetic**
 - Exchange Bias
- **Hard / Soft Ferromagnetic**
 - Exchange Spring Magnets
- **Ferromagnetic / Non-magnetic**
 - Giant Magnetoresistance
 - Spin-injection
- **Ferromagnetic / Superconducting**
 - Proximity Effects
- **Ferromagnetic / Ferroelectric**
 - Artificial Multiferroics
- ...

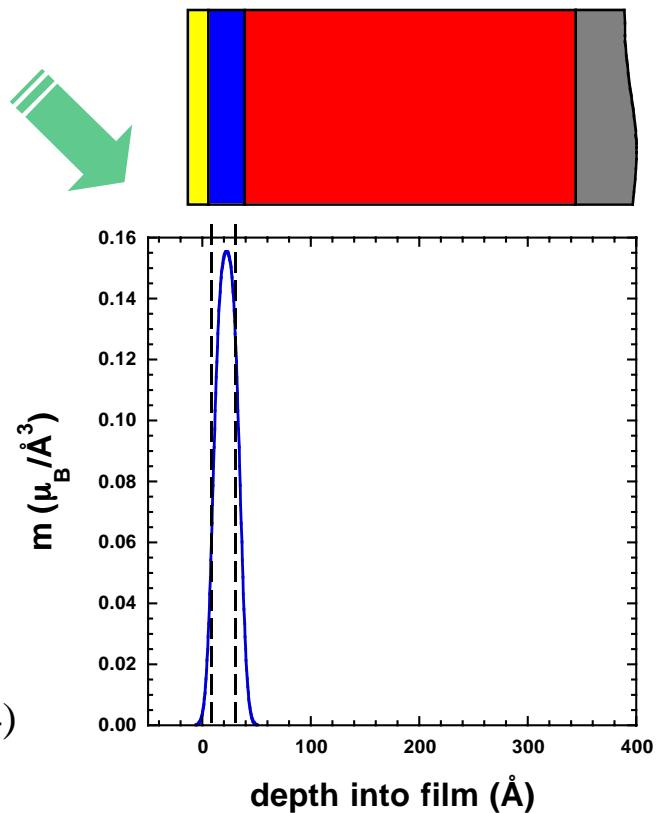


In all these cases a detailed understanding
of the magnetic structure is paramount!

Polarized Neutron Reflectometry



Deduce
Magnetization
Depth Profile
from Model Fitting

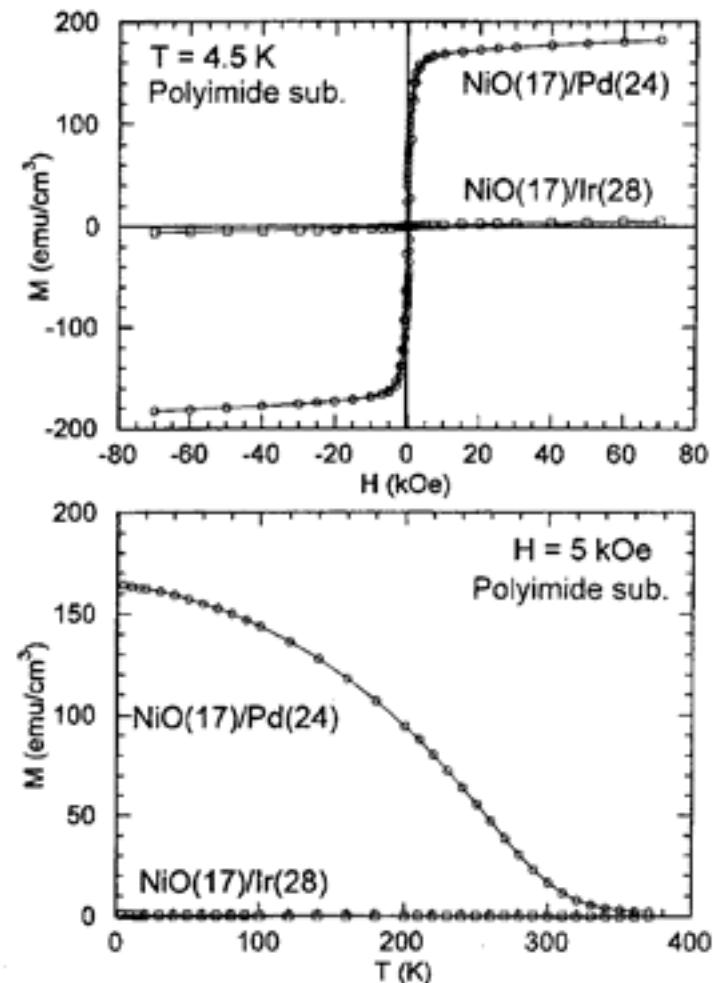
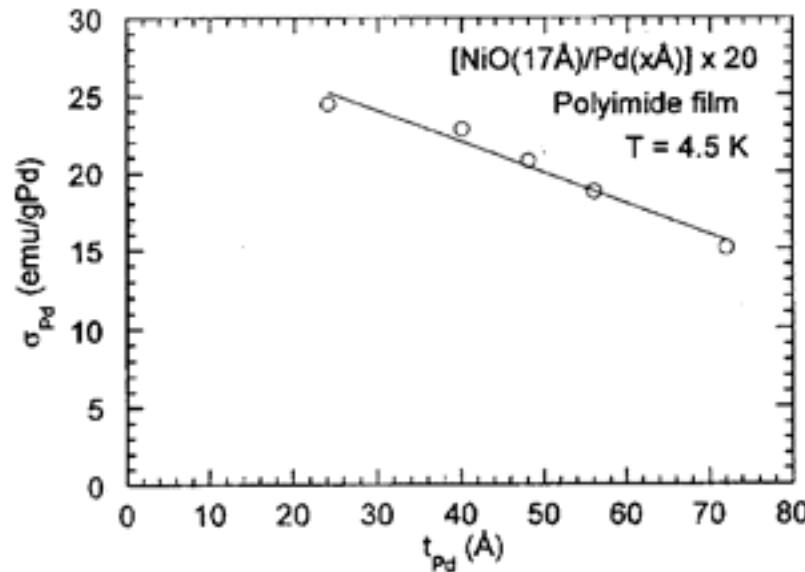


M. R. Fitzsimmons, *et al.*, J. Magn. Magn. Mater. **271**, 103 (2004)

Equilibrium Magnetization Structures

- **Can Antiferromagnets induce Ferromagnetism?**
 - Pd on NiO
- **Why is the Magnetization suppressed in oxide based Superconducting / Ferromagnetic Superlattices?**
 - $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ / $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$
- **Is there a net magnetic moment in the antiferromagnet of an exchange bias system?**
 - Co / LaFeO_3

Does Pd on NiO become ferromagnetic?

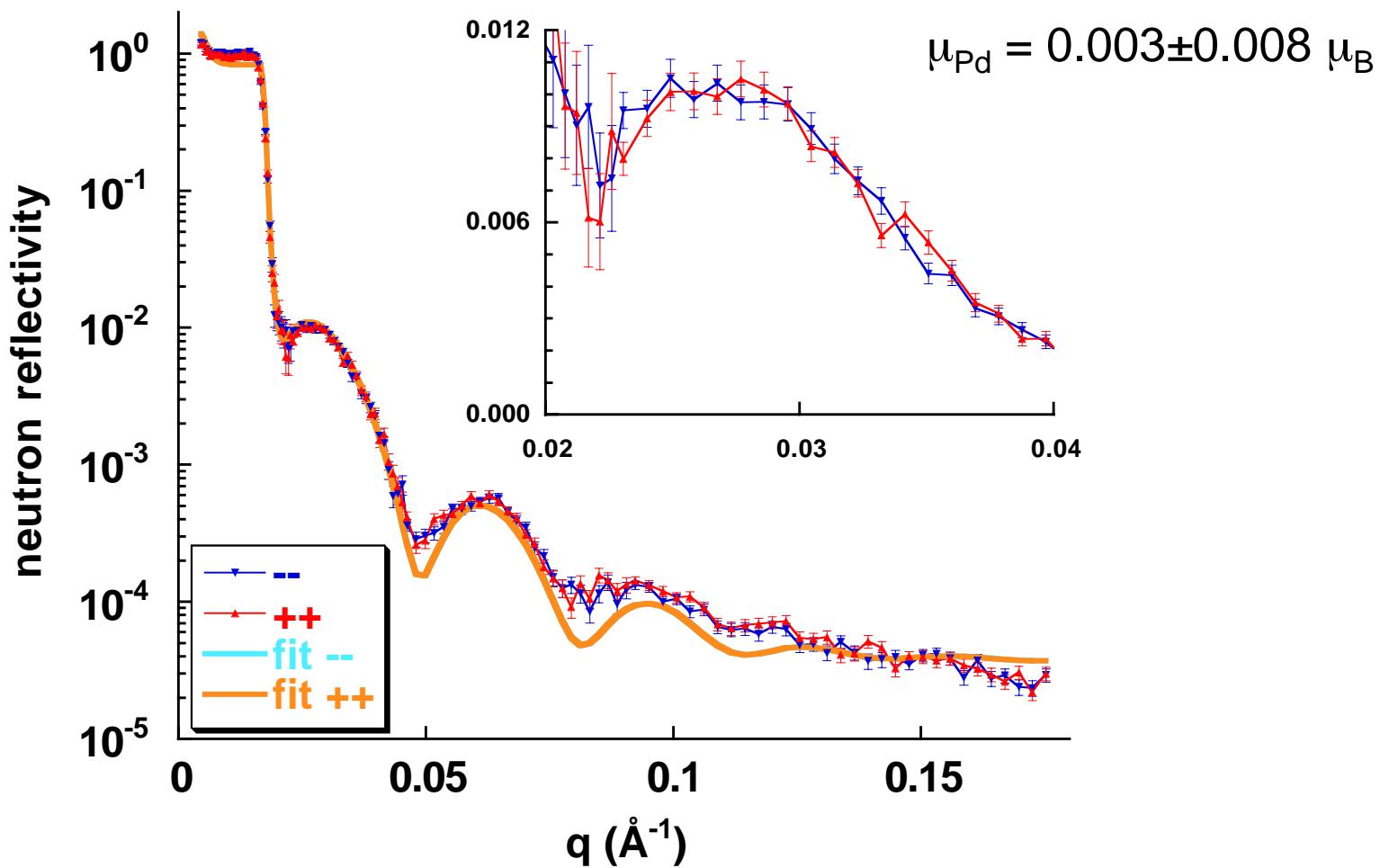


Suggests indirectly:

- $\mu_{\text{Pd}} = 0.59 \mu_B$ at interface
- decays within 35 Å

T. Manago, *et al.*, J. Phys. Soc. Jpn **68**, 334 (1999)

No, it does not!

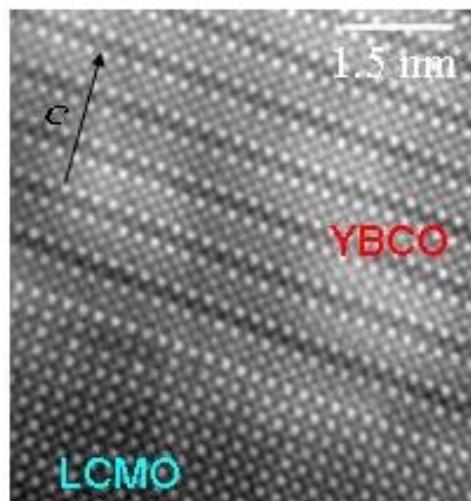


A. Hoffmann, *et al.*, Phys. Rev. B **65**, 024428 (2002)

Element specificity of X-rays is very well suited to this problem

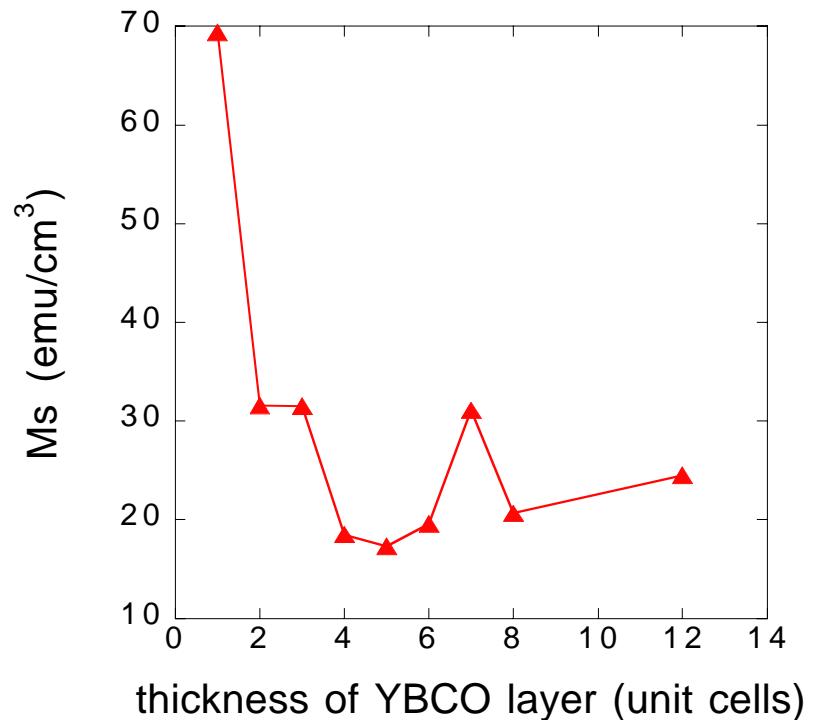
$YBa_2Cu_3O_{7-\delta}$ / $La_{0.7}Ca_{0.3}MnO_3$ Superlattices

Structurally
very sharp interfaces



Roughness down
to one unit cell

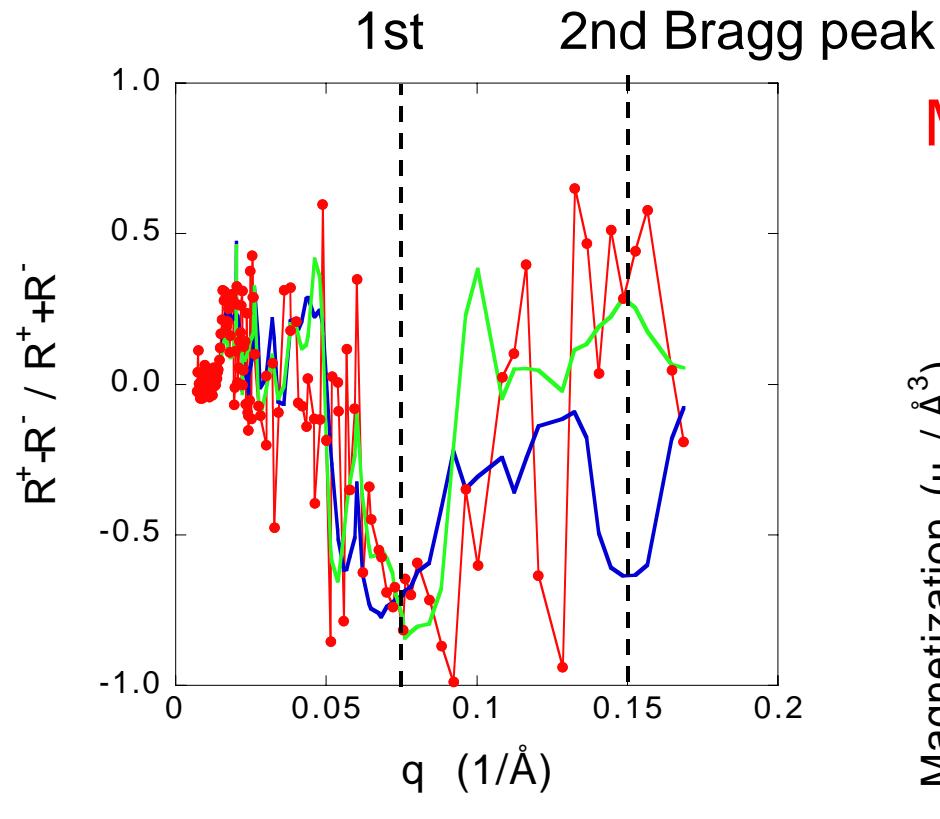
Magnetization is suppressed



LCMO bulk:
 $M_s = 576$ emu/cm³

Typical value for
single layer thin films:
 $M_s = 400$ emu/cm³

Magnetization is suppressed at Interface

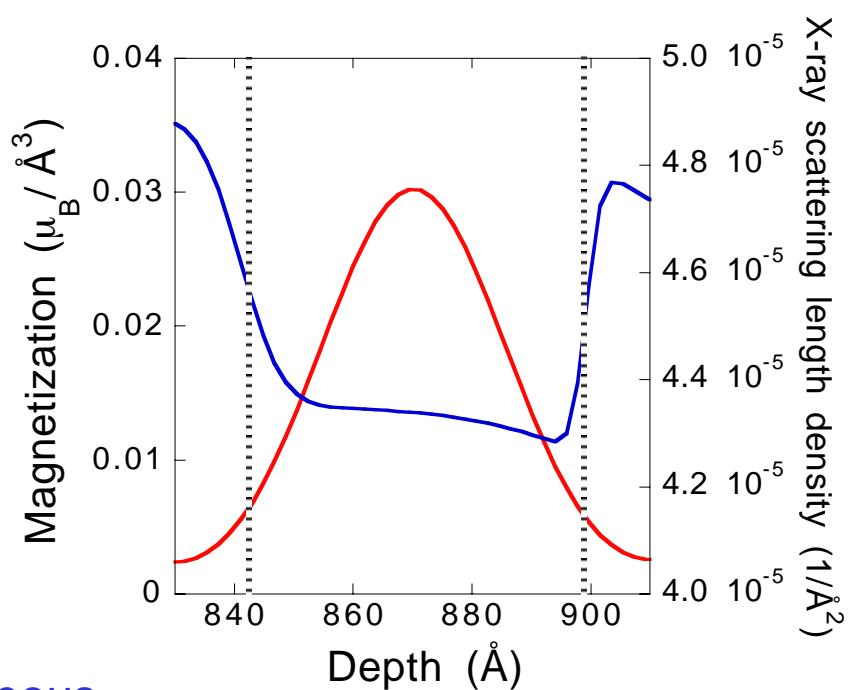


Best Fit:

Inhomogeneous
Magnetization

Homogeneous
Magnetization

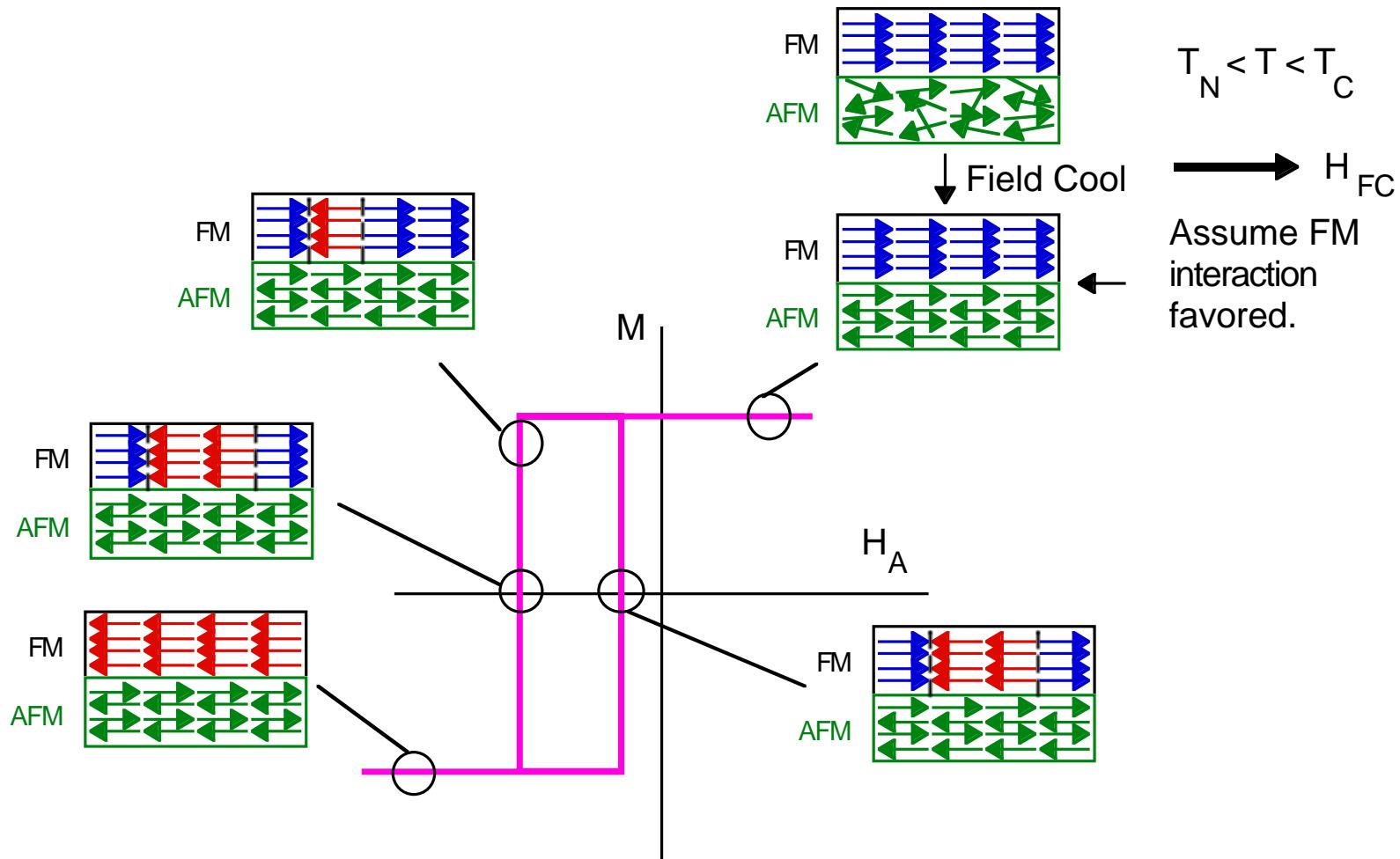
Magnetization Depth Profile
One single LCMO layer



X-rays could probe potential antiferromagnetic order at interface



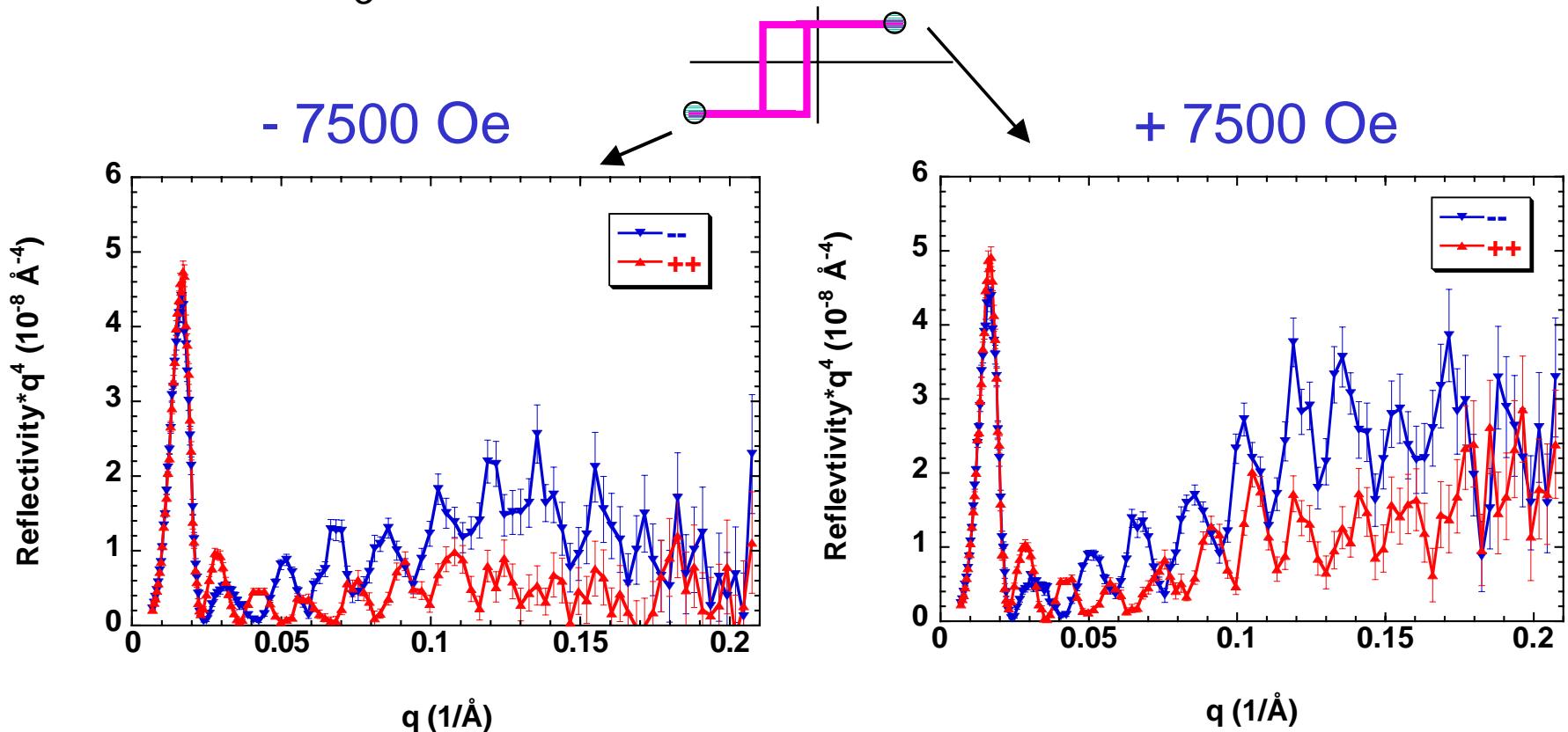
Exchange Bias



- W.H. Meiklejohn, C.P. Bean, Phys Rev., **105**, 904(1957).
- J. Nogués, Ivan K. Schuller, J. of Magn. Magn. Mater., **192**, 203 (1999).

Net Moment in Antiferromagnet

Co on LaFeO₃ measured at 18 K



- Net Moment of $2\mu_B/\text{Fe}$ within 10 Å of interface
- Antiferromagnetically coupled to ferromagnet

A. Hoffmann, *et al.*,
Phys. Rev. B **66**, 220406(R) (2002)

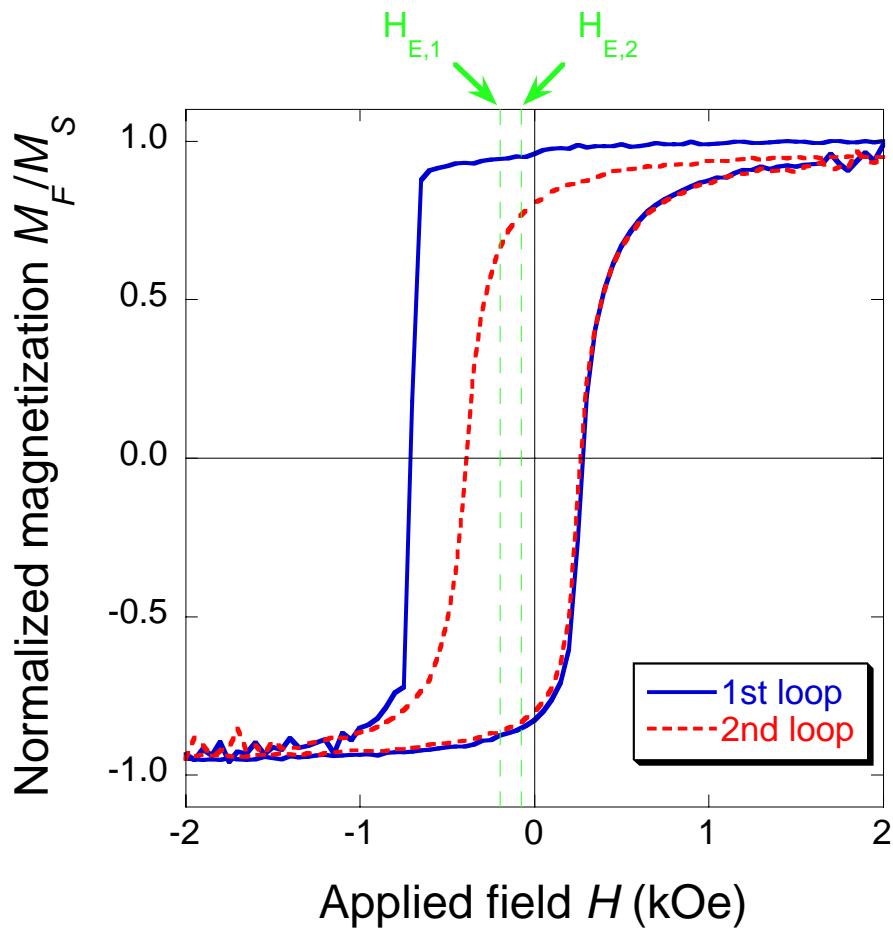
Use X-rays to track magnetic field dependence

Non-Equilibrium Situations

- **Metastable Magnetization Configurations**
 - Training Effects in Exchange Bias Systems
- **Spin-injection into non-magnetic materials**
 - Lateral Spin-Valves

Training Effects in Exchange Bias Systems

Co/CoO at 10 K



Training observed

$\text{CoO}, \text{FeO}, \text{FeMn}, \text{Ir}_{22}\text{Mn}_{78},$
 $\text{KCoF}_3, \text{NiFeMn}, \text{NiO}, \text{PtPdMn},$
 $\text{La}_{0.3}\text{Ca}_{0.7}\text{MnO}_3$

No Training observed

$\text{FeF}_2, \text{MnF}_2$

Suggests that symmetry of
anisotropy in the
antiferromagnet is important
for training effects

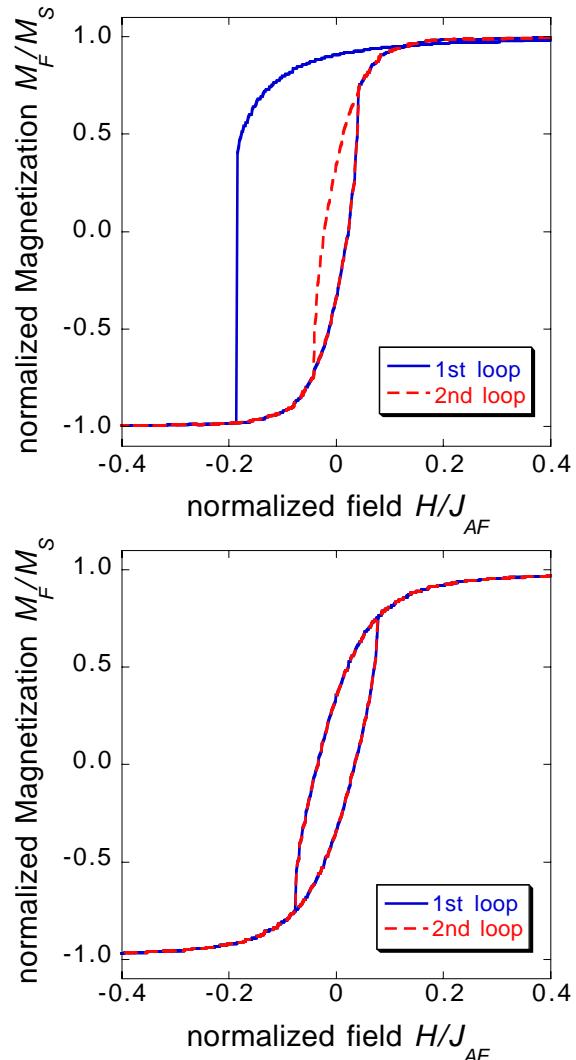
Calculated Hysteresis Loops

Biaxial
Anisotropy

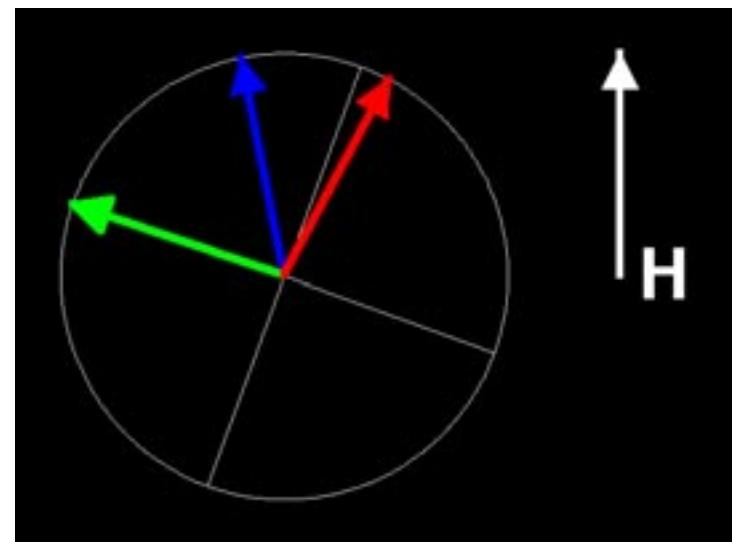
Training!

Uniaxial
Anisotropy

No Training!



First Hysteresis Loop

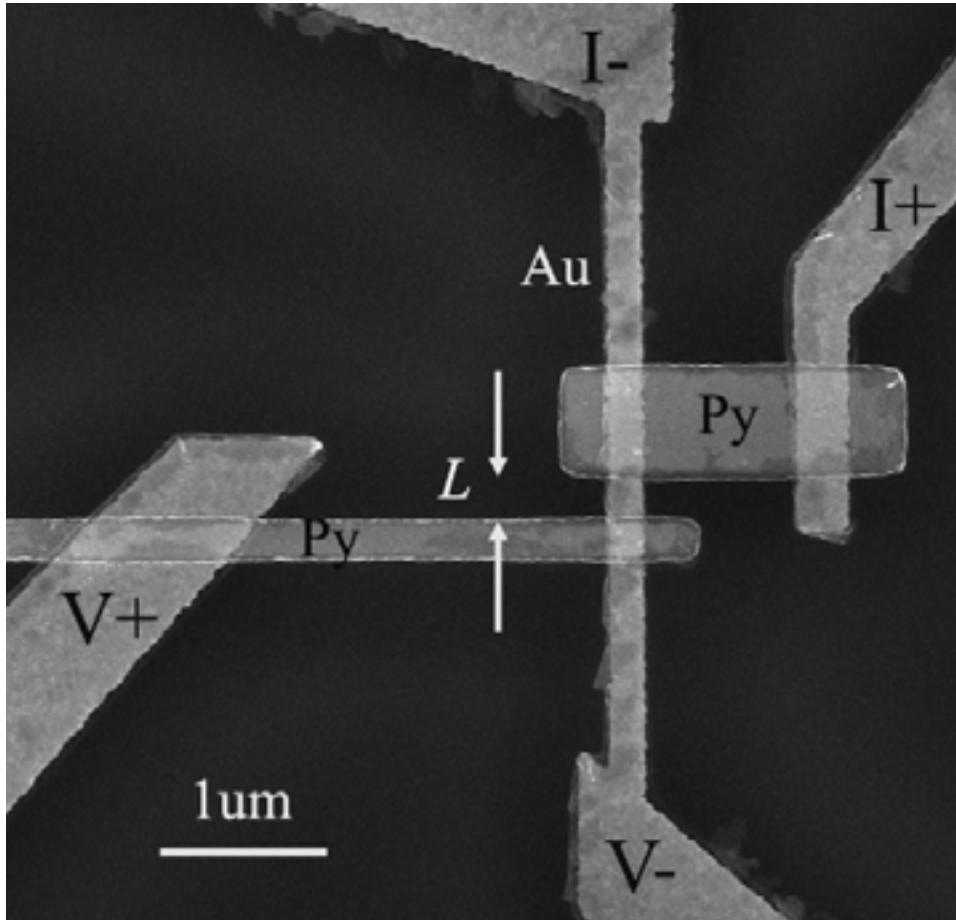


↑↑ Antiferromagnetic Spins
↑ Ferromagnetic Magnetization

A. Hoffmann,
Phys. Rev. Lett. (to be published)

Detect change of net moment in antiferromagnet with X-rays

Lateral Spin-Valves



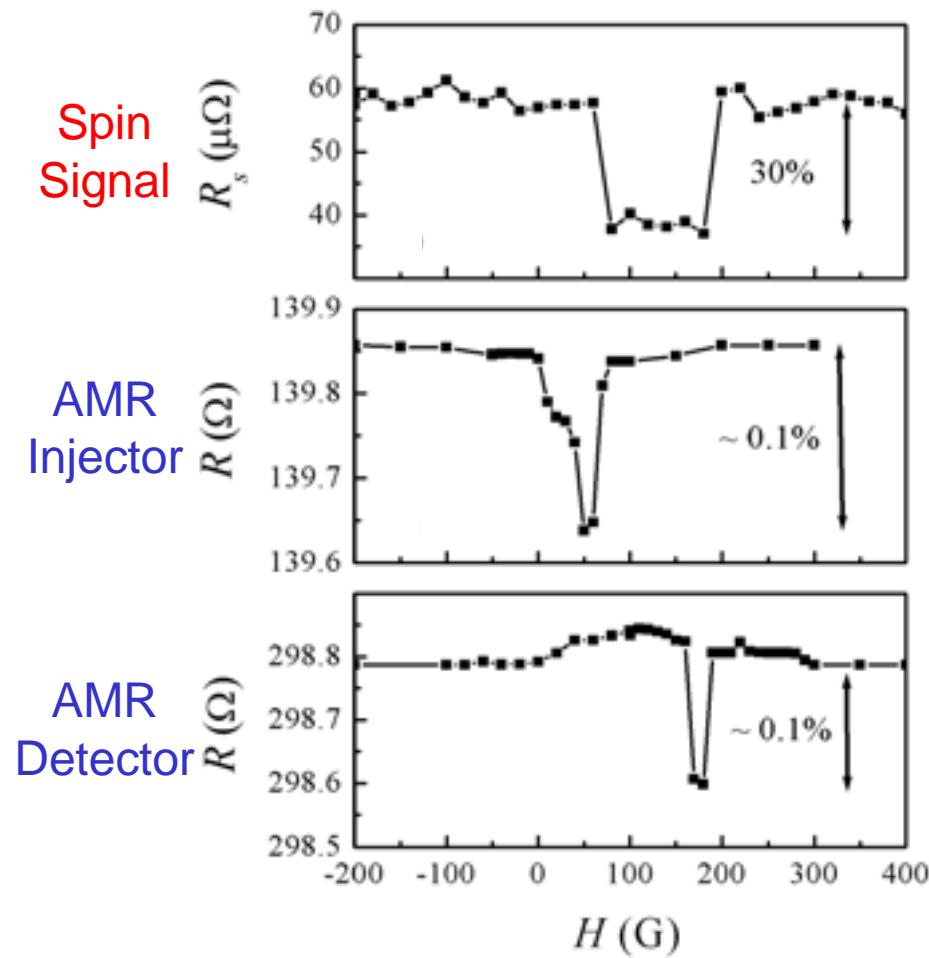
2-dimensional structures
give additional
flexibility for
magnetotransport

Allows planview of
interfaces

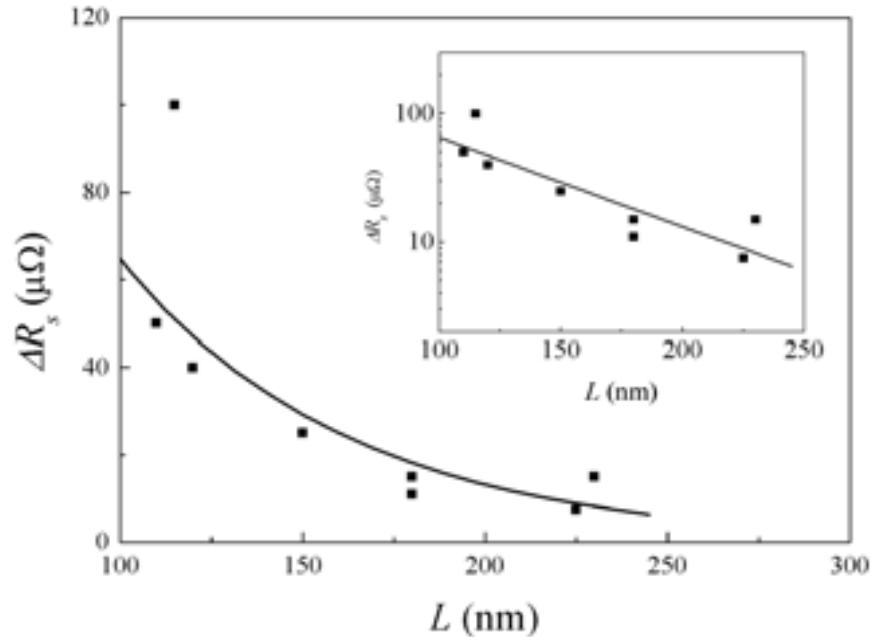
Typical dimensions
around 100 nm
⇒ easily accessible by
most X-ray microscopies

Yi Ji, *et al.*,
submitted to Appl. Phys. Lett.

Spin-Injection



Distance Dependence



$$\lambda_S = 63 \pm 15 \text{ nm at } 10 \text{ K}$$

Yi Ji, *et al.*,
submitted to Appl. Phys. Lett.

Image spin-diffusion directly with X-rays, i.e., PEEM+XMCD

Thanks to

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\$\$\$ DOE-BES and MCYT \$\$\$



Conclusion

- **Magnetization structure at interfaces is important for many current problems in magnetism**
 - Exchange Bias
 - Magnetotransport
 - Proximity effects
- **Plenty of opportunities for X-ray techniques**
 - Element specificity
 - Measurements of hysteresis loops
 - Real-space imaging